ZERO-GRAVITY FLAMMABILITY

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ABSTRACT

A study of flammability in a zero-g environment, based on results obtained during aircraft flight, is discussed. The need for long-duration zero-g testing to study inflight spacecraft fire propagation, safe spacecraft designs, and methods of fire extinguishment is shown. The objectives of Apollo Applications Program Experiment M-479 (which concerns flammability in zero g and the equipment needed for the experiment) are discussed.

INTRODUCTION

A two-phase series of experiments was conducted to study the effects of weightlessness or zero g on a flame. This program was undertaken so that the seriousness of an accidental fire in a spacecraft could be evaluated and the means of controlling such a fire could be developed.

Available literature contains only two references regarding flammability in zero g. In 1956, Kumagai and Isoda (ref. 1) reported on the combustion of droplets in a falling chamber. Their data showed that, as the droplet diameter decreased, the flame diameter increased. The maximum test time was 0.32 second. In 1963, Hall (ref. 2) observed a burning candle in aircraft tests with zero-g intervals lasting as long as 25 to 28 seconds. On the basis of some thermocouple data and the change of the flame coloration to deep blue, he concluded that the flame was somewhat hotter than characteristic of one g. Both works indicated that a steady-state condition existed.

ZERO-g FLAMMABILITY — PHASE I

A comparison between flames in one- and zero-g environments is shown in figure 1. When a hydrocarbon is burned in one g, several events occur simultaneously. Solid material is converted to hot gases, thereby absorbing energy. The gases mix with the surrounding atmosphere and, in chemically reacting with the oxygen, liberate energy. Hot gas products are formed, including carbon dioxide, carbon monoxide, water vapor, and numerous minor constituents ranging from hydrogen to complex acids, alcohols, and other organic compounds. These products are formed through various intermediates, including atoms and free radicals. The high temperature of these gases contributes to the low density. The gases rise from the flame zone, allowing more oxygen to enter and mix with the fuel gases. Thus, a steady-state combustion process, in which gas flow-in can be equated with gas flow-out, is made possible.

An idealized concept (based on experimental results) of zero-g combustion is shown in figure 1 as the flame achieves a maximum degree of burning. It should be emphasized that the depicted condition is transitory. As the films of combustion in a zero-g environment show, the flame builds up to a maximum size and brilliance soon after ignition, then quickly recedes, and darkens. The experimental flame never achieved the total envelopment depicted for two reasons: The igniter localized the burning to a few spots and the products of combustion tended to subdue the flame before the fuel could be enveloped.

Several aspects of the zero-g flame are noteworthy. The gas that is formed by an overheated material in zero g is ignited and burns in the oxygen with which the gas is initially mixed. The fuel-to-air ratio, therefore, changes during combustion from lean to rich as the ambient oxygen is depleted. This depletion occurs much more rapidly than the diffusion process can supply oxygen. Eventually, oxygen starvation occurs and the flame begins to cool by radiation and conduction. What results is a blanket of unburned flammable gases adjacent to a solid or molten fuel that, in turn, is covered with a layer of both solid and gaseous combustion products with a very low oxygen content. The result is that the fire is diminished to the extent that light is no longer visible, which indicates that steady-state combustion was not achieved. Thus, oxygen can be less than an inch away from warm flammable gases, yet be unable to react with the gases. These conclusions were based on the pictures showing the flame darkening and diminishing less than 1.5 seconds after ignition. In the familiar one-g environment, the flame temperatures invariably increase over a brief period to a peak heat when steady-state combustion is achieved. Zero-g burning is hampered because only the fuel gases generated within extremely brief periods can burn. In many instances, the flame itself is apparently too cool to generate additional flammable gases.

In several instances of paraffin burning, the light disappeared for several seconds and reappeared when an acceleration returned and convection developed (e.g., when weightlessness ceased because the experiment chamber came into contact with the aircraft). It is assumed when the light is no longer visible that the fire is extinguished with respect to energy emittance, because neither the color nor the infrared film used in the experiments revealed any evidence of combustion during these intervals. With respect to chemical unbalance, however, the system is better described as dormant, with the intermediate free radicals remaining where formed. When convection was renewed, molecular oxygen reacted with these free radicals as the hot, light gases flowed away from the fuel and the process resumed.

The data pertinent to most of the tests shown in the motion-picture film are listed in table I; 26 burnings were photographed. Fuels included spacecraft materials and paraffin (selected because of the relatively simple chemical structure and kinetics). The atmospheres used included pure oxygen, air, and other oxygen-nitrogen mixtures. Pressures varied from 5 psia, as used in manned spacecraft, to 14.7 psia. Styrene, white foam rubber, and paraffin were used as fuels in the nine burnings shown in this presentation. Excess oxygen was present and the fuel was burning during the return to level flight in all instances.

The equipment designed for the experiments is shown in figure 2. These flammability chambers were designed for use in aircraft tests. The 15 chambers were designed to be charged with a selected fuel and atmosphere under controlled conditions so that the inflight time could be used to the best advantage and so that gas products could be analyzed after the flight.

The equipment used in the first series of tests consisted of a shell of anodized aluminum with a volume of 0.75 cubic foot (which provided a region 10 inches in diameter for the flame), a glass window to permit photography of the combustion, and a fuel support that allowed positioning of the fuel without obstructing the atmosphere or flame. The support was made of glass beads threaded on a wire. A filament made of 20-gage Nichrome wire was positioned horizontally from two brass electrodes. Twenty-four volts dc were passed through the wire to ignite the fuel; the voltage overloaded the wire and caused a break in approximately 2 seconds, which opened the circuit. The fuel could be contacted at a single point or in several places. The points of contact appeared to start separate fires, some of which united. A grid 5 inches behind the fuel provided 0.25-inch parallel lines for reference. No supplemental light was used; in fact, the aircraft cabin was usually dark during the tests.

FILM NARRATION

Zero-g flammability was observed by using a Wright-Patterson Air Force Base aircraft equipped for weightless flight. The first scene shows the interior of the C-131. The camera and ignition plugs of the control cable are shown being connected to a flammability chamber by an engineer. A sample "float" lasting 8 seconds is shown next. Some floats lasted slightly longer than 8 seconds; the maximum measured time in this series of tests was 12 seconds.

Several tests showing ignition and combustion during zero g are shown next. These scenes, photographed at 200 frames per second, are being shown in slow motion at one-eighth the actual time. The horizontal member is the ignition wire.

Styrene

First, styrene was ignited in zero g in 100 percent oxygen at 5 psia. The fires started at several points. The flame increased rapidly and then began to darken and diminish before the wire parted. The fire spread slowly, causing some of the smaller fires to unite. Meanwhile, the rate of combustion continued to diminish with the passage of time until the chamber struck the aircraft cabin, ending the test.

Foam Rubber

Foam rubber in the same atmosphere is shown next. The foam rubber took longer to ignite and the ignition wire parted less than 1 second after ignition. A very uniform flame corona can be seen, with flowing particles of carbon passing through a sharp interface in a completely random distribution. The dark shadow in the center of the flame is unburned fuel. Again, the corona diminished and darkened before the period of weightlessness ended.

Paraffin

Paraffin was used as a control fuel. The paraffin was ignited in zero g in 21 percent oxygen at 14.7 psia. The heated gas quickly ignited and then appeared to be extinguished. The wire can be seen to part and cool approximately 0.5 second after ignition. The actual time that passed before the flame reappeared was 5.7 seconds (for this showing, no blank film has been deleted). Little information about what occurred during this interval is available. No emitted energy is detectable in the color film used here nor in the infrared film used in the final scene. It is evident that the region containing the fuel cooled by both radiation and conduction. The Nichrome wire darkened and eventually became invisible. When the period of weightlessness ends (in any direction or magnitude), the hot products of combustion flow from the flame zone as

fresh oxygen flows in. In this series of tests, the flame invariably reappeared as the force field was renewed so that in every case except for Teflon, the fuels were burning during the return to level flight. Whether this reignition occurs because of the heat load or because the gases remain reactive or chemically hot — that is, contain numerous free radicals with unpaired electrons that reacted with the molecular oxygen — has not been determined. Another possibility is the presence of a "cool flame," but a cool flame is usually detectable by the deep purple color. Regrettably, the zero-g time was not of sufficient duration in this series of tests for a fire, once extinguished, to remain extinguished. Several other paraffin-fuel flammability tests were similarly documented. Most tests exhibited the same self-extinguishment seen here.

Paraffin was again ignited as before, except that in this test pure oxygen was used. The corona was small, as in the first two scenes, which also were photographed in a 100-percent-oxygen environment. The higher oxygen pressure seemed to make very little difference as compared with the 5-psia pressure. The flame diminished, darkened, and appeared to be extinguished as before. The appearance of the flame at the upper portion of the fuel resulted from the location of the igniter wire, not from an induced motion at the time of ignition.

Next, paraffin was ignited in an atmosphere of 50 percent oxygen/50 percent nitrogen at 10 psia, which equates to the same partial pressure of oxygen as in the first two scenes of styrene and foam rubber. Again the flame had the darker, less well defined corona that diminished very rapidly, apparently because of the presence of the inert gas. The fire appeared to be extinguished, but when the package was struck, convection resumed momentarily; then weightlessness reoccurred and again the fire appeared to be extinguished until the effect of the final impact with the aircraft was observed.

Another combustion of paraffin in a 100-percent-oxygen atmosphere at 14.7 psia is shown for comparison. This portion of the film shows the dramatic effect of several impacts on the molten fuel.

Paraffin in a 50-percent-oxygen/50-percent-nitrogen mixture at 10 psia was again ignited.

Infrared film was used to record two burnings in an attempt to obtain a qualitative temperature measurement. This burning (and the next) used paraffin in 100 percent oxygen at 5 psia. The pictures were taken at 100 frames per second. Thus, the viewing speed has been doubled to one-fourth the actual time of the two scenes. The same coronal diminution occurred until an acceleration (as indicated by the vibration) was imposed.

In this last test of paraffin burning in oxygen, the atmosphere was the same as used before. Again, the fire appeared to be extinguished very shortly after ignition, as can be seen quite easily in these infrared views.

DISCUSSION OF AIRCRAFT TESTS

The temporary extinguishments seen in the film indicate the possibility that a dormant, fairly cool envelope of chemically reactive gases remains in the flame zone; the gases ignite only if the oxygen contacts the fuel. In time, if left undisturbed, oxygen slowly entering this zone by diffusion could combine with the reactive products without increasing the temperature. In many tests, gas samples were removed and analyzed. One gas of special concern was carbon monoxide. Although not detected in samples burned in one g, carbon monoxide was found in three of the 18 zero-g test analyses for this gas. This incidence of carbon monoxide is not surprising, however, when one considers the over-rich condition resulting from the zero-g environment. Results of the Phase I test series are discussed in reference 3.

ZERO-g FLAMMABILITY — PHASE II

The burning rates of various materials investigated in the second series of tests are shown in table II. Five polymeric materials were selected as fuels. Four materials (neoprene, silicone, Teflon, and polyurethane) represent electrical insulation; the fifth material (Dacron thread wrapped around polyurethane) was tested for possible use in space suits. All fuels were tubular to eliminate variations caused by geometrical shape. Three test atmospheres were selected — ambient air, pure oxygen at 5 psia, and pure oxygen at 15 psia. One- and zero-g data are compared.

The equipment used in the Phase II tests was basically the same as that used in the Phase I tests except for the fuel configuration. Ignition was provided by a resistance wire closely wrapped around one end.

It should be noted that, despite the variety of burning rates in one g, the zero-g rates are approximately 0.1 in/sec for oxygen atmospheres (table II).

CONCLUSIONS

1. Ignition during periods of weightlessness is essentially unchanged compared with ignition in one g.

2. Burning rates are reduced to approximately 0.1 in/sec for a wide assortment of solid hydrocarbon fuels.

3. Self-extinguishment can occur in some fuel-atmosphere systems.

4. Introduction of an acceleration renews convection promptly.

5. A distinct gas interface exists at the edge of the corona, which implies a phenomenon analogous to surface tension, with characteristics varying according to the presence of inert gases.

The need for exploring the effects of longer periods of weightlessness is obvious. Several methods have been proposed, including free-fall drops from towers or aircraft and the use of rockets, X-15 aircraft, or unmanned Apollo spacecraft.

The current approach of sharing equipment with other experiments is described in reference 4. The objectives of this experiment are the following items with respect to burning various materials in pure oxygen at 5 psia.

1. Extent of flame propagation, flashover to adjacent materials, et cetera

2. Rates of surface- and bulk-flame propagation under zero-g convection

3. Self-extinguishment

4. Extinguishment by vacuum or water spray

Only one atmosphere is to be used in the tests, although a variety of atmospheres have been proposed for future use, and despite the fact that the most interesting results in the aircraft tests were noted in two-gas atmospheres. Similarly, relatively few materials can be selected for test fuels and only limited fire-extinguishment data will be obtained. Thirty-seven tests are proposed. All tests will be photographed with 16-millimeter motion-picture film at the rate of 24 frames per second.

Although the presently scheduled test program is severely limited in scope, it is recognized that a more thorough program is desirable. Much valuable information could be derived from tests of wider scope. For example, ignition energies and spectral patterns during the initial period of self-extinguishment should provide very useful data. Tests using gaseous fuels and metals (which produce only solid ash instead of gaseous combustion products) burning in zero-g conditions could also be conducted. The apparent surface tension existing between the luminous plasma and the surrounding gas also should be investigated further. All these test objectives, of course, cannot be included in the M-479 Experiment.

Hopefully, space flight will afford many hours of zero-g environment for testing and will provide engineering data that can be used not only for designing future spacecraft, but also for solving some of the mysteries of the combustion mechanisms on earth.

REFERENCES

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2. Hall, A. L.: Observations on the Burning of a Candle at Zero Gravity. Bureau of Medicine and Surgery Project MR005.13-1002, Subtask 11, Research Rept. No. 5, U.S. Naval School of Aviation Medicine, Pensacola, Fla., Feb. 26, 1964, 4 pp.

3. Kimzey, J. H.; Downs, W. R.; Eldred, C. H.; and Norris, C. W.: Flammability in Zero-Gravity Environment. NASA TR R-246, 1966.

4. Kimzey, J. H.: Experiment Inplementation Plan for Manned Space Flight Experiments — Zero Gravity Flammability, Experiment M-479. Aug. 8, 1969.

TABLE I.- ZERO-g FLAMMABILITY EXPERIMENTS

Test no.	Fuel	Weight, gram	Oxygen atmosphere, percent	Nominal pressure, psia	Zero-g time, sec	Photography
16	Styrene	1.0003	100	5	--	Color
15	Foam rubber	.2706	100	5	6	Color
35	Paraffin	.7213	[a]21	14.7	10	Color
19	Paraffin	.1084	100	14.7	5 to 8	Color
56	Paraffin	.1636	[b]50	10	7 to 12	Color
28	Paraffin	.1244	100	14.7	5	Color
36	Paraffin	.1551	[b]50	10	3 to 8	Color
22	Paraffin	.1524	100	5	--	Infrared
10	Paraffin	.5680	100	5	3	Infrared

[a]Atmosphere consisted of air of 60 ± 10 percent relative humidity.

[b]Dry nitrogen constituted the remaining 50 percent of the atmosphere.

TABLE II.- BURNING RATES IN ONE g AND ZERO g

Fuel (b)	Rate of burning, in/sec (a)					
	One g			Zero g		
	Air at 15 psia	Oxygen at 5 psia	Oxygen at 15 psia	Air at 15 psia	Oxygen at 5 psia	Oxygen at 15 psia
Neoprene	0.0	0.2	0.4	--	0.10	--
Silicone	.04	.5	1.1	0.0	.08	--
Teflon	.0	--	--	--	.00	--
Polyurethane	--	.6	.7	.0	.08	0.15
Dacron[c]	--	.6	.7	--	.08	.15

[a]Ignition was provided by electric resistance coil; the temperature of the atmosphere was 65° ± 5° F.

[b]Fuel was tubular (no. 10 American wire gage i.d.) and threaded over a steel or ceramic mandrel.

[c]Dacron thread was wrapped around polyurethane.

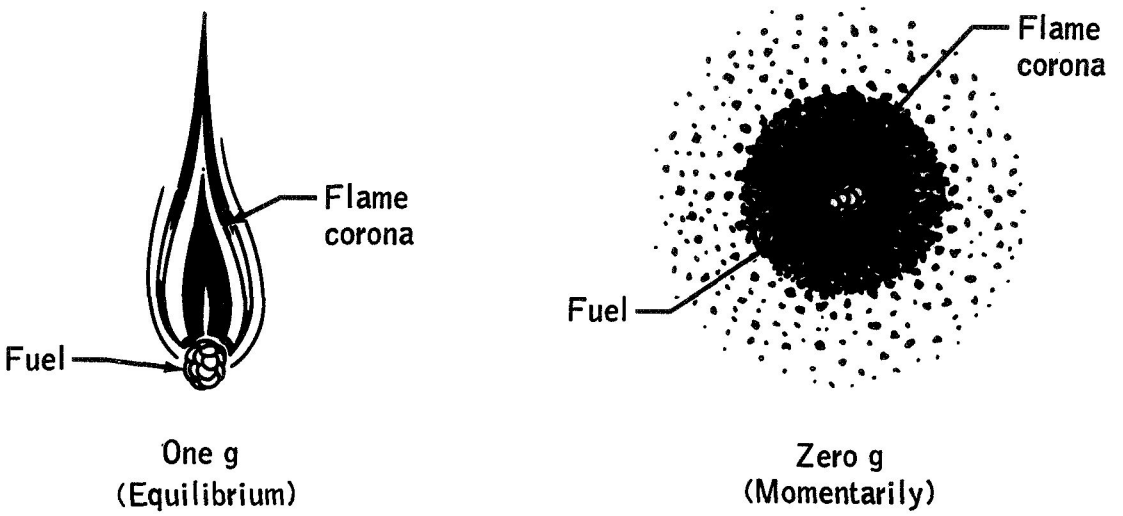

Figure 1.- Comparison of fuel burning at one-g and zero-g in oxygen atmosphere.

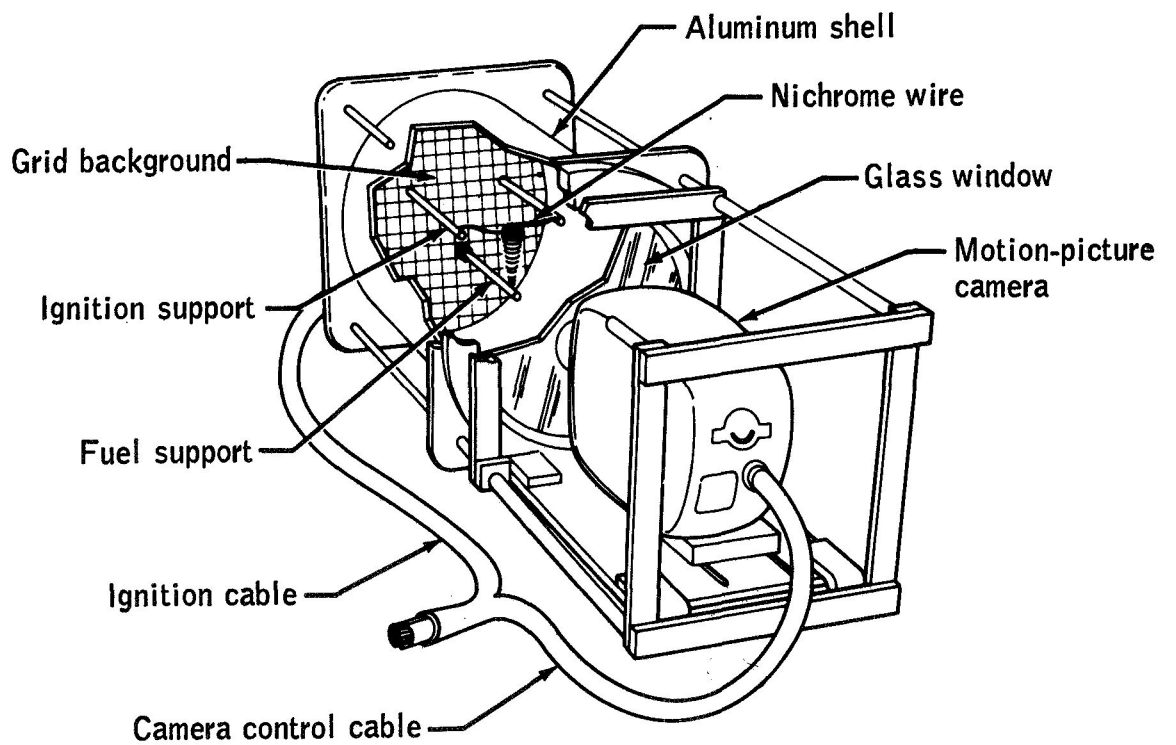

Figure 2.- Zero-g flammability chamber.

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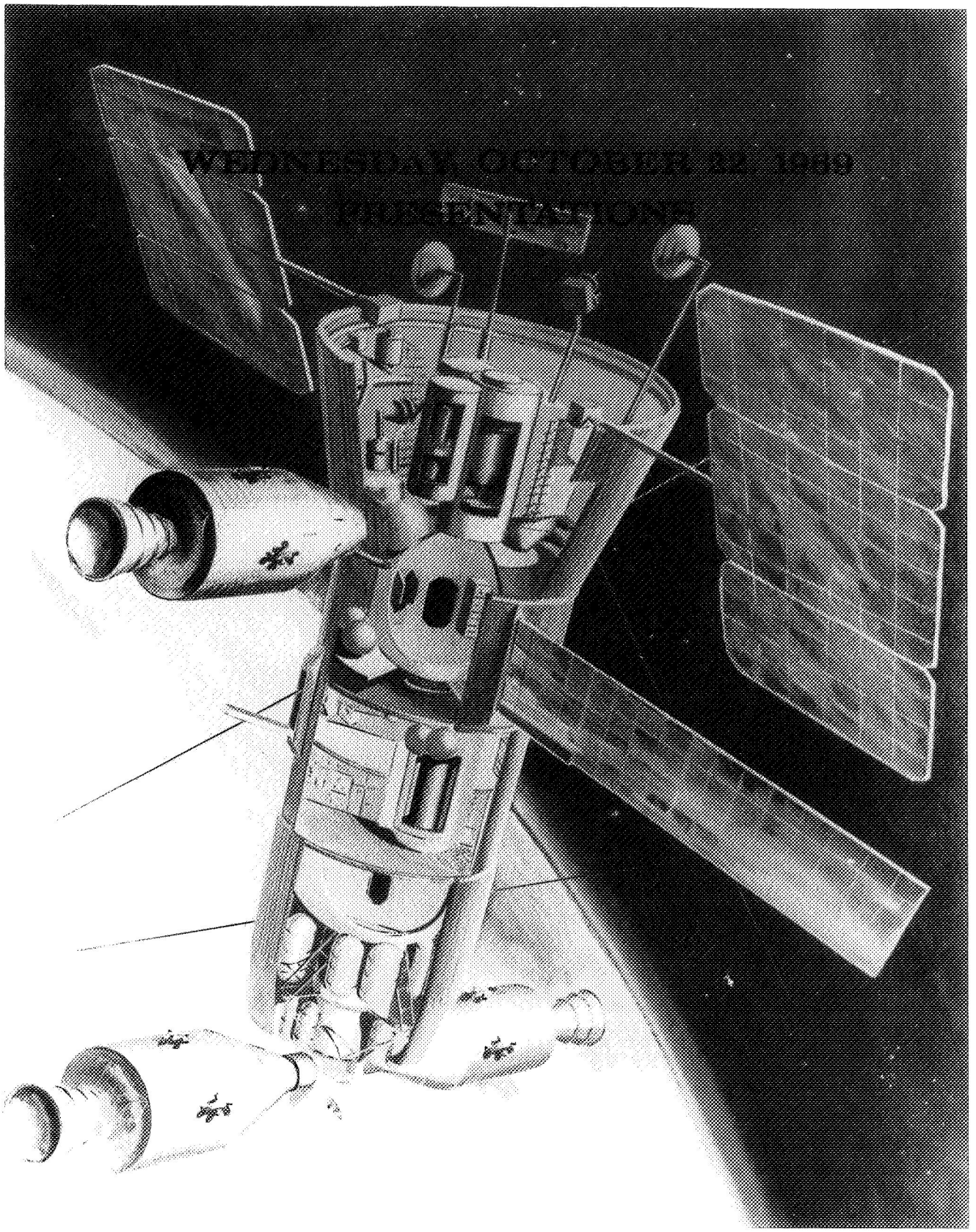
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